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# Monolithic photonic integration technology platform and devices at wavelengths beyond 2 μm for gas spectroscopy applications

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## ABSTRACT

In this paper a generic monolithic photonic integration technology platform and tunable laser devices for gas sensing applications at 2 μm will be presented. The basic set of long wavelength optical functions which is fundamental for a generic photonic integration approach is realized using planar, but-joint, active-passive integration on indium phosphide substrate with active components based on strained InGaAs quantum wells. Using this limited set of basic building blocks a novel geometry, widely tunable laser source was designed and fabricated within the first long wavelength multi-project wafer run. The fabricated laser operates around 2027 nm, covers a record tuning range of 31 nm and is successfully employed in absorption measurements of carbon dioxide. These results demonstrate a fully functional long wavelength photonic integrated circuit that operates at these wavelengths. Moreover, the process steps and material system used for the long wavelength technology are almost identical to the ones which are used in the technology process at 1.5μm which makes it straightforward and hassle-free to transfer to the photonic foundries with existing fabrication lines. The changes from the 1550 nm technology and the trade-offs made in the building block design and layer stack will be discussed.

**Keywords:** Photonic Integrated Circuits, semiconductor laser, tunable laser, gas spectroscopy

## 1. INTRODUCTION

Generic photonic integration technologies allow for design and fabrication of photonic integrated circuits (PIC) at reduced research and development efforts[1]. Such technology platforms rely on a limited set of predefined, standardized functions for on-chip manipulation of light which are made available in a form of building blocks (BB). These BBs can be used by application oriented users to design and realize large complexity application specific photonic integrated circuits (ASPIC). Currently available and mature generic technology platforms offer their functionalities at wavelengths window around 1.5 μm which corresponds to the c-band in the area of telecommunications. Consequently majority of the ASPICs which are being realized using such technologies target this area of applications[1]. In order to widen the scope of possible applications and extend a potential market for such generic photonic integration technologies accessible wavelength bands have to be diversified[2,3]. The mid-infrared wavelengths beyond 2 μm are in particular attractive for the applications in gas spectroscopy[4,5] which is related to the presence of absorption profiles of several gas species in this wavelengths range. For example trace analysis of gases like acetone, ammonia, carbon dioxide[5], water vapor, formaldehyde, diethylamine, ethylamine and methylamine is important in a wide range of applications including environmental monitoring in agriculture, process control in chemical and pharmaceutical facilities, atmospheric pollution monitoring and for medical screening and diagnosis. The use of a photonic integration technology allows for the co-integration of source and detection sub-systems on a single chip which is an attractive alternative for gas detection systems where complexity and size of bulk optics based solutions is a prohibitive factor[3,4]. A number of technologies giving an access to the long wavelength ranges at 2 μm and beyond has been reported in the literature[6–11] with demonstrations of monolithic[12] and heterogeneous[13–17] photonic integration technologies. Although setting the state-of-the-art in terms of reported performance those are based on highly customized processes and frequently require an

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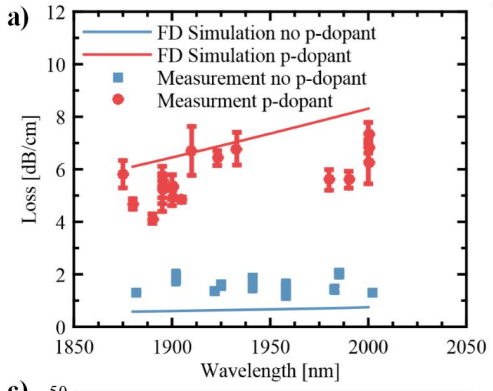
addition of new materials to the process. The long wavelength integration technology platform presented here is almost identical to the standard technology process used for fabrication of photonic integrated circuits and devices at 1.5 µm and can be easily adopted by a foundry having such process in place. In order to extend the potential of already existing generic integration technology at 1.5 µm by adding access to the wavelengths above 2 µm a developments of a monolithic, active-passive integration on indium phosphide (InP) substrate have been undertaken at the COBRA research institute[18]. These efforts allowed for the first successful fabrication of a long wavelength multi-project wafer run (MPW)[1,19]. In this MPW widely tunable lasers sources operating at such long wavelengths were realized as a monolithic InP based photonic integrated circuits[20,21]. The capability of the fabricated laser for high resolution scanning is demonstrated in a single-line spectroscopy experiment with a carbon dioxide reference cell[22].

## 2. LONG WAVELENGTH ACTIVE-PASSIVE INTEGRATION TECHNOLOGY

Photonic integration technology developed in the COBRA research institute is a planar, monolithic active-passive integration on indium phosphide substrate. In this generic technology the BBs are realized on one of the two types (active or passive) of vertical epitaxial cross-sections combined on a common InP substrate via butt joint integration [1]. In order to realize all basic functionalities at the wavelengths beyond 2 µm a development process of the COBRA long-wavelength technology included modifications of the active and passive layer-stacks and adaptations of all BBs. The early stage studies and experiments have shown that at such longer wavelengths an increase in the propagation losses[23,24] and lower modal gain[18] values shall be expected. The simulated and measured propagation losses in the passive waveguides are presented in the Figure 1(a). Main contribution to the increase of the optical losses at longer wavelengths is attributed to the increased overlap of an optical mode with the highly doped cladding layers. In order to reduce this effect the thickness of the wave-guiding layer was increased from 500 nm used in standard technology to 625 nm with further adjustments of the ridge waveguide (RWG) structures. The RWG widths were increased to 2.0 µm and 2.5 µm for deep and shallow waveguides respectively.




b)

| Thickness | | Active | Passive |
|---|---|---|---|
| 600 nm | | Au | |
| 150 nm | | Ti/Pt/Au | |
| 300 nm | | InGaAs ($1.5*10^{19}$cm$^{-3}$ P) | |
| 1000 nm | | InP ($10^{18}$ cm$^{-3}$ P) | |
| 500 nm | | InP ($10^{17}$ cm$^{-3}$ P) | |
| Wave-guiding core - 625nm | 218.0 nm | $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$ | $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$ |
| | 37.5 nm | $In_{0.53}Ga_{0.47}As$ | |
| | 6.0 nm | $In_{0.78}Ga_{0.22}As$ strained QW | |
| | 30.0 nm | $In_{0.53}Ga_{0.47}As$ | |
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| | 6.0 nm | $In_{0.78}Ga_{0.22}As$ strained QW | |
| | 37.5 nm | $In_{0.53}Ga_{0.47}As$ | |
| | 218.0 nm | $In_{0.74}Ga_{0.26}As_{0.57}P_{0.43}$ | |
| 70.0 nm | | InP (undoped) | |
| 430.0 nm | | InP ($5.0*10^{17}$ cm$^{-3}$ N) | |
| 300 µm | | InP (substrate) | |

Figure 1. (a) Simulated and measured propagation losses in passive waveguides at long wavelengths [19]. (b) A schematic diagram of the active and passive layer stacks used for fabrication of the long wavelength multi-project wafer run. (c) Net modal gain of ridge waveguide semiconductor amplifier based on strained quantum wells and fabricated using optimized ridge waveguide geometry.



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Generation and amplification of light at the wavelengths around 2 μm has been demonstrated previously with use of strained InGaAs quantum well[25–27] and quantum dash[28] based material systems grown on InP substrates. An extended wavelength range up to 1.8 μm of an InP active–passive photonic integration technology platform has been demonstrated in COBRA research institute with use of quantum dots, targeting applications in optical coherence tomography[29]. Developments of this integration technology platform towards even longer wavelength were based on strained quantum wells material [18,26]. A new optically active core based on low temperature (560 °C) grown strained quantum wells has been developed. It features multiple quantum well (MQW) structure with five periods of stained QWs (InGaAs) and barriers (InGaAsP) positioned centrally in the wave guiding layer. The epitaxial layers of the vertical cross-sections of long wavelength active and passive waveguides used for the definition of basic building blocks are shown schematically in Figure 1 (b). Shallow and deep etched RWG structures are used on the passive layer-stack to form passive BBs (waveguides, splitters and combiners, electro refractive modulators). Only shallow type of the RWG is used on the active structures to realize BBs which provide means of light generation, amplification and absorption (photodiodes, saturable absorbers). Net modal gain measured from such RWG semiconductor optical amplifier (SOA) fabricated using this new technology is presented in Figure 1(c).

These research and development efforts allowed to carry a fabrication of the first long-wavelength multi-project wafer (MPW) run. The 2" wafer included 8 designs from 5 different users and projects, including two novel types of integrated tunable laser sources with a wide tuning range above 2 μm wavelength[20–22].

## 3. WIDELY TUNABLE LASER SOURCE.

Using this new long wavelength integration technology a widely tunable laser with an intra-cavity wavelength filter based on asymmetric Mach-Zehnder interferometers (AMZI) has been realized[30]. The device follows a similar concept fabricated using the standard COBRA integration technology platform at 1.5 μm which demonstrated a record performance in terms of the tuning range and was shown to be suitable for the single line gas spectroscopy [31,32]. The long wavelength laser uses tunable wavelength selective intra-cavity AMZI filter in a nested configuration as presented schematically in Figure 2 (a). The combination of two inner AMZI stages with unbalances $\Delta L_1 = 2110$ μm and $\Delta L_2 = 16$ μm with and additional unbalance $\Delta L_3 = 74$ μm in the outer interferometer effectively results in six unbalances. The wavelength tuning is achieved by controlling four electro refractive modulators (ERM) introduced into the inner AMZIs. Due to mutual dependencies between the unbalanced stages the intra-cavity filter in such configuration requires more complex tuning strategy when compared to the serial configuration [32] but it allows one to reduce the overall cavity length and lower the roundtrip loss which was desired in view of the increased propagation losses in the passive and active waveguides. The multimode interference (MMI) couplers are used to form interferometers and also to couple out signals from the laser cavity.

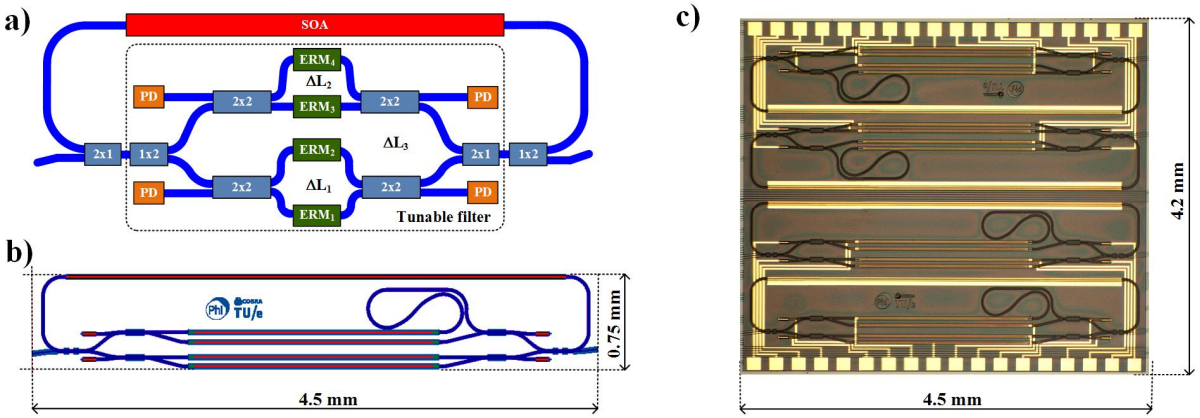


Figure 2. (a) A schematic diagram of the ring laser featuring an intracavity tunable wavelength filter based on nested asymmetric Mach-Zehnder interferometers (dotted box)[24]. The photonic integrated circuit (PIC) consists of several basic building blocks connected with passive waveguides (in blue): a semiconductor optical amplifier (SOA), multimode interference couplers (1x2, 2x2 MMI), electro refractive modulators (ERM) and photodiodes (PD). (b) A mask layout of the tunable laser[24]. (c) A microscope image of a long-wavelength chip. The 20 $mm^2$ PIC was fabricated within a multi-project wafer run and includes four tunable lasers[24].



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The overall laser cavity length with this type of the wavelength filter and 4 mm long semiconductor optical amplifier (SOA) section is around 9 mm with a corresponding free spectral range of 9 GHz. The mask layout of a laser with the nested AMZI filter configuration is shown in the Figure 2 (b). A long wavelength chip of 20 $mm^2$ including four of such lasers has been fabricated within a multi-project wafer run using such long-wavelength technology. A microscope image of the chip of 20 $mm^2$ is presented in Figure 2 (c).

The fabricated chip was mounted on water cooled metal block and temperature of the heat sink was kept at 18 °C for all experiments discussed. The tunable laser was operated under DC current injection into the SOA section and at room temperature conditions. The LVI characteristic presented in Figure 3 (a) shows a threshold current density of 3.4 kA/$cm^2$ and a slope resistance of 5 Ω. The device delivers around 0.1 mW of average optical output power coupled into the single mode lensed fiber (~0.3 mW ex-facet assuming a fiber coupling loss of ~5dB). The AMZI filter in a nested configuration allows for a record tuning range of 31 nm at around 2027 nm which can be seen from the overlapped optical spectra recorded with a resolution of 0.05 nm in Figure 3(b). Such tuning bandwidth is achieved by applying a reverse bias voltage to four electro refractive modulators (ERM) in the arms of the nested AMZI while the current injection into the SOA section and the temperature of the chip are being held constant. The laser was single-mode over the whole tuning range with the side-mode suppression ratio (SMSR) of at least 30 dB.

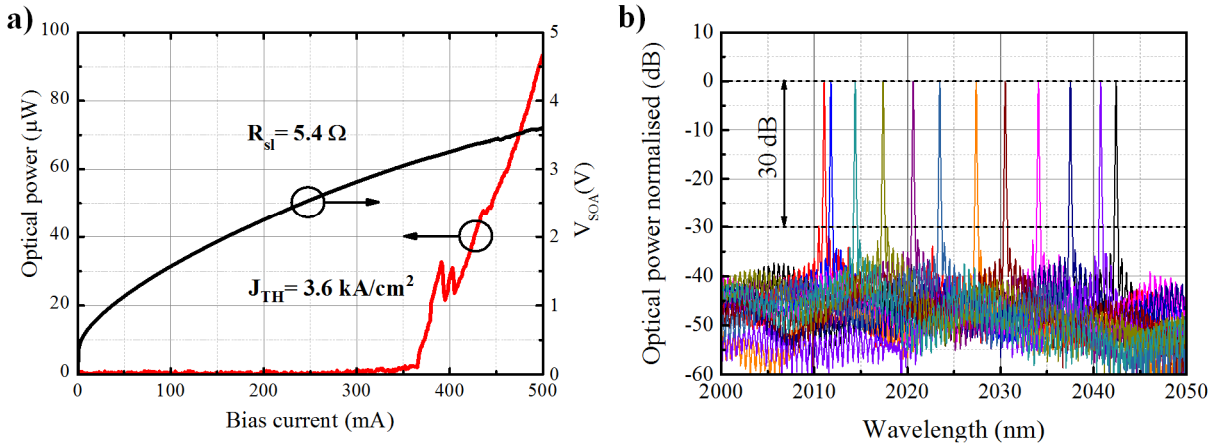


Figure 3. (a) The LVI characteristics of the long wavelength integrated laser. The VI profile indicates a slope resistance of around 5 Ω and the LI shows a lasing threshold at current density of 3.4 kA/$cm^2$. (b) Optical spectra recorded for a series of sets of reverse voltages applied to the ERMs with the injection current into the SOA and temperature constant at $I_{SOA}$ = 450 mA and T= 18 °C respectively.

## 4. GAS SPECTROSCOPY EXPERIMENT

The long wavelength tunable laser has been employed in a basic gas spectroscopy experiment carried using a reference gas cell filled with carbon-dioxide. The output from the laser was distributed between probe and reference optical paths using a fiberized optical coupler (50:50). The reference signal was used to monitor any intensity fluctuations with a photodiode. The probe signal was collimated into the free space beam and sent through a $CO_2$ gas cell followed by another photodetector. The cylindrical reference cell was filled with $CO_2$ at 0.1 atm (Precision Glassblowing TG-ABCO2-Q) had 10 cm long interaction region and 19 mm diameter. The input and output windows were angled at 2 degrees. The laser was tuned to target a particular absorption line by using reverse voltage applied to the ERMs and swept over by applying changes of current injection into the gain section. The SOA current was swept from 420 to 490 mA in discrete steps of 0.25 mA which resulted in a wavelength tuning over 14 GHz with the frequency step of 50 MHz (676 fm). This tuning range was wider than the free spectral range between cavity modes and no mode-hops were observed. Five discrete, consecutive transition lines were measured as presented in Figure 4 (a). In the Figure 4 (b) the central absorption line is presented in details and overlapped with the absorption spectrum of carbon-dioxide simulated using the HITRAN [33] database and parameters of the reference gas cell. Each absorption line of carbon-dioxide with the conditions of the reference cell features a full-width at half maximum of around 0.9 GHz.



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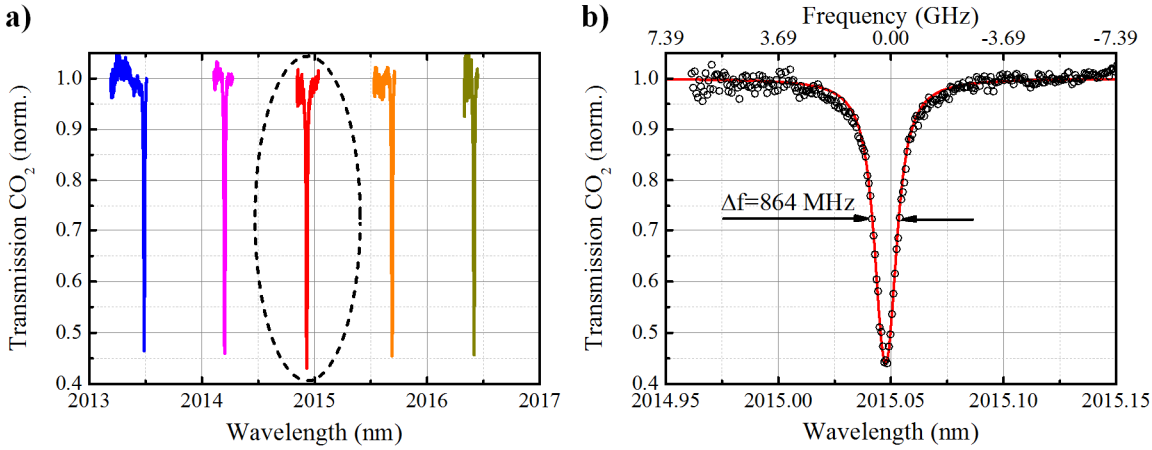


Figure 4. (a) Five discrete and consecutive absorption lines of carbon-dioxide recorded using the long-wavelength PIC laser. (b) Detailed view of the central line (black circles) overlapped with the absorption profile simulated (solid red line) with the HITRAN software using parameters of the reference gas cell used for the experiment[22].

## 5. SUMMARY

A monolithic photonic integration technology platform developed in the COBRA research institute functional at wavelength band beyond 2 µm has been presented. Such long wavelength functionality paves the way for new application areas for such technologies in particular in gas spectroscopy. Developed technology uses almost identical process steps when compared to the standard fabrication process at 1.5 µm and can be easily adopted by InP foundries. Using this generic integration technology a widely tunable laser was designed and realized. An application specific photonic integrated circuit chip with four of such lasers has been fabricated on a shared wafer basis within a first multi-project wafer run using that technology. The fabricated laser shown a wide tuning range of 32 nm and has been demonstrated to be suitable for a single line gas spectroscopy systems.


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